LCA Case Studies

Life Cycle Assessment Study of Biopolymers (Polyhydroxyalkanoates) Derived from No-Tilled Corn

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Abstract

Goal and Scope. This study attempts to estimate the environmental performance of Polyhydroxyalkanoates (PHA), from agricultural production through the PHA fermentation and recovery process – 'cradle to gate'. Two types of PHA production systems are investigated: corn grain based PHA and corn grain and corn stover based PHA.

Methods. Corn cultivation data are taken from 14 counties in the Corn Belt states of the United States – Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin. The environmental burdens associated with the corn wet milling process, in which dextrose, corn oil, corn gluten meal and corn gluten feed are produced, are allocated to dextrose and its coproducts by the system expansion approach. Greenhouse gases include carbon taken up by soil, nitrous oxide (N_2O) released from soil during corn cultivation, carbon contents in biobased products as well as carbon dioxide, methane and nitrous oxide released from industrial processing. The soil carbon and nitrogen dynamics in corn cultivation are predicted by an agro–ecosystem model, the DAYCENT model. The environmental performance of the PHA production system is compared to that of a conventional polymer fulfilling an equivalent function. The environmental performance is addressed as nonrenewable energy and selected potential environmental impacts including global warming, photochemical smog, acidification, and eutrophication. The characterization factors are adapted from the TRACI model (Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the United States Environmental Protection Agency.

Results and Discussion. Global warming associated with corn grain based PHA is 1.6–4.1 kg-CO_2 eq. kg^{-1}. The primary contributing process to most environmental impacts except for photochemical smog and eutrophication is the PHA fermentation and recovery process. For photochemical smog and eutrophication, the primary contributing process is corn cultivation due to nitrogen related burdens from soil. The trend of PHA fermentation development shows that the PHA fermentation technology is still immature and continues to improve, thereby also decreasing the environmental impacts. PHA produced in an integrated system, in which corn stover is harvested and used as raw material for PHA along with corn grain, offers global warming credits (negative greenhouse gas emissions), ranging from –0.28 to –1.9 kg-CO_2 eq. kg^{-1}, depending on the PHA fermentation technologies employed and significantly reduces the environmental impacts compared to corn based PHA. The significant reductions from the integrated system are due to 1) less environmental impacts in corn cultivation and wet milling, and 2) exporting surplus energy from lignin–rich residues in corn stover process.

Conclusions and Outlook. Under the current PHA fermentation technology, corn grain based PHA does not provide an environmental advantage over polystyrene. Corn grain based PHA produced by the near future PHA fermentation technology would be more favorable than polystyrene in terms of nonrenewable energy and global warming due to improvement in the PHA fermentation and recovery process. However, corn grain based PHA produced in even the near future technology does not provide better profiles for other environmental impacts (i.e., photochemical smog, acidification and eutrophication) than polystyrene. One of the primary reasons for high impacts of PHA in photochemical smog, acidification and eutrophication is the environmental burdens associated with corn cultivation. Thus other approaches to reduce these burdens in the agricultural process (e.g., use of buffer strips, etc.) are necessary to achieve better profiles for photochemical smog, acidification and eutrophication associated with corn cultivation. PHA produced in the integrated system is more favorable than polystyrene in terms of most environmental impacts considered here except for eutrophication.

Keywords: Biopolymers; corn; corn stover; polyhydroxyalkanoates; pha; soil organic carbon; wet milling

Introduction

Biopolymers are generally considered as environmentally friendly materials in terms of biodegradability and use of renewable resources. A primary market driving force for biopolymers is the perceived scarcity of fossil resources, especially petroleum. Most conventional polymers currently available are made from crude oil. Plant materials have been recognized as a renewable alternative resource to replace fossil resources. For example, ethanol derived from corn grain is a widely used transportation fuel with the potential to save large amounts of petroleum–derived fuels (Wang et al. 1999, Kim and Dale 2002). Polylactide (NatureWorks™ PLA) polymers derived from corn grain produced by Cargill Dow LLC (Minnetonka, Minnesota, USA) are commercially available to make products ranging from packaging materials to apparel (Vink et al. 2003). Polyhydroxyalkanoates (PHA), made from plant–based dextrose, are used as a packaging film that may also be alternatively made from conventional polymers (e.g., polyethylene (PE) or polystyrene (PS)) (Heyde 1998).

Previous studies have attempted to scrutinize the nonrenewable energy consumption and greenhouse gas profile of biopolymers. Gerngross (1999) estimated the fossil fuel equiva-

lent (FFE) for producing PHA from corn and compared it with polystyrene (PS) from petroleum, concluding that the FFE of PHA was slightly larger than that of PS. He also concluded that using fermentation-derived PHA would not appear to be a sustainable approach. Kurdikar et al. (2001) pointed out that corn stover-based PHA resin produced using fossil fuel sources had no greenhouse gas advantage over polyethylene (PE) resin. Kurdikar et al. (2001) also found that using biomass energy from corn stover in the PHA system, instead of nonrenewable energy, would result in a better greenhouse gas profile for PHA resin than for PE resin.

Recently Akiyama et al. (2003) performed a life cycle inventory analysis of PHA derived from soybean and from corn grain, which concluded that PHA is more favorable than petroleum based polymers in terms of energy use and greenhouse gas emissions. These authors credited the carbon content in PHA in the greenhouse gas emission analysis. Cargill Dow LLC (Vink et al. 2003) also carried out an LCA study on their product (NatureWorks™ PLA) and found that the PLA production system consumes 22–55% less nonrenewable energy than petroleum based polymers. The greenhouse gas emissions associated with the PLA production system are less than or comparable to those of petroleum based polymers. If wind power replaces grid electricity used in a biorefinery, or if bioenergy from corn stover is used in generating steam for a biorefinery, PLA has much better environmental performance than petroleum derived polymers in terms of fossil fuel energy and greenhouse gas emissions.

Thus, the studies of Gerngross (1999) and Akiyama et al. (2003) arrive at completely different conclusions. The main reasons for these differences are the allocation approach used in the corn wet milling process, PHA yield during fermentation, and the operational data in the PHA fermentation and recovery process. Gerngross (1999) and Akiyama et al. (2003) allocated the environmental burdens of wet milling to dextrose and its coproducts on a mass basis. Gerngross (1999) failed to allocate the environmental burdens associated with the input (corn grain) to dextrose and its coproducts. These burdens should be allocated in a consistent way. Failing to assign the burdens associated with corn production to dextrose may lead to inconsistent results. Akiyama et al. (2003) did not include soil carbon and nitrogen dynamics in the agricultural ecosystem. Agricultural ecosystem effects could play an important role in analyzing greenhouse gas emissions from corn production.

1 Goal of Study

This study attempts to estimate the environmental performance of PHA, from agricultural production through the PHA fermentation and recovery process – 'cradle to gate'. The PHA production system derived from corn grain is defined as the reference system. We also estimate the environmental performance of the PHA production system derived from both corn grain and corn stover, a crop residue, (called an 'integrated system'). The environmental performance of the PHA production system is compared to that of a conventional polymer fulfilling an equivalent function (i.e., packaging film).

2 Methods

The function of the product system is defined as polymer used in a packaging film. We chose 1 kg of PHA resin as the reference flow. The system boundary in the reference system includes corn production, dextrose production (corn wet milling), PHA fermentation and recovery process, and upstream processes (e.g., fertilizers, agrochemicals, fuels, electricity, etc.). In addition to the system boundary of the corn grain-based PHA system, processes for producing PHA derived from corn stover (e.g., harvesting and transporting corn stover, PHA production process from corn stover) are included in the system boundary in the integrated system. The system boundaries are summarized in **Fig. 1**. Management of PHA wastes is not included in the system boundary because the fate of waste PHA is not clear at this point. Thus, the analysis has been done from cradle to gate.

The corn wet milling process is a multi-output process, in which dextrose, corn oil, corn gluten meal (CGM) and corn gluten feed (CGF) are produced together. The allocation is done by introducing avoided environmental burdens of al-

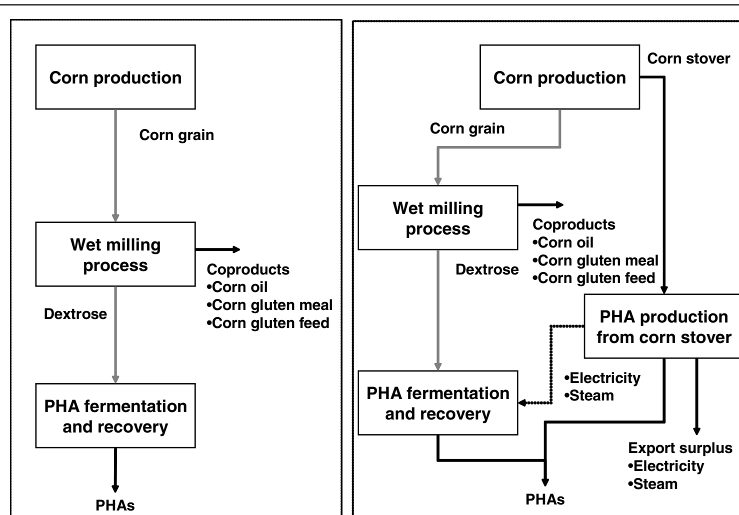

Fig. 1: System boundary of the PHA production systems. (A) reference system and (B) integrated system

ternative products for the wet mill coproducts – this is called the 'system expansion' (International Organization for Standardization 1998). The alternative product for corn oil is soybean oil produced in soybean milling, in which soybean meal is also produced. The environmental burdens of soybean oil are also estimated from the system expansion approach (Kim and Dale 2002). The alternative products for CGM and CGF, which are used as animal feeds, are corn grain and nitrogen in urea, with their appropriate replacement factors (Wang 2000). For example, the function of one kg of CGF is equivalent to the functions of one kg of corn and of 15 g of nitrogen in urea. Soybean oil is an alternative product for corn oil. The environmental burdens of soybean oil are estimated from soybean milling process (Sheehan et al. 1998). Effects of the physical property based allocation approach on the final results are also investigated in a sensitivity analysis.

Lignin–rich residues are generated during corn stover processing to PHA (Kurdikar et al. 2001). These residues can be burned to generate electricity and steam, which can be used within the system. The efficiency of generating electricity from biomass in an integrated gasification combined cycle power plant is about 32%, and the efficiency of generating steam is 51% (Stahl and Neergaard 1998). Surplus steam could be exported to replace energy used in a district heating system, in which natural gas and heating fuel are assumed to be the energy source, and surplus electricity would be exported to a regional power grid as seen in Fig. 1.

Most processes are assumed to occur in the United States. The corn production sites are specified and occur in 14 counties in the Corn Belt states of the United States – Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin. The primary factors governing selection of corn production sites are as follows: 1) the local region could supply a local crop producing facility, 2) regions are quite different agronomically and 3) even within a state, agronomic characteristics can be different. The corn production of the two selected counties in each states ranges from 4–12% of the total corn production of that state. Corn wet milling and PHA fermentation are assumed to occur at the same location. Corn is assumed to be grown under no–till practice, in which soil is left undisturbed from harvest to planting. The fraction of no-tilled cornfield in the Corn Belt states is about 18% (Conservation Technology Information Center 2004). Data for corn production, including agronomic inputs and fuel used, are available from the United States Department of Agriculture (National Agricultural Statistics Service 2004, Economic Research Service 2003). **Table 1** summarizes agronomic inputs and fuel used in corn cultivation under no-till practice. The values in Table 1 are weighted by corn production.

Table 1: Agronomic inputs and fuel used under no-till practice per year

	Unit	Quantity
Corn grain yield	metric ton ha^{-1} (wet)	9.00
Nitrogen fertilizer	N kg ha^{-1}	176.42
Phosphorous fertilizer	P_2O_5 kg ha^{-1}	78.00
Potassium fertilizer	K_2O kg ha^{-1}	88.07
Herbicides	kg ha^{-1}	3.47
Insecticides	kg ha^{-1}	0.17
Lime	kg ha^{-1}	32.39
Diesel	MJ ha^{-1}	959.77
Gasoline	MJ ha^{-1}	277.02
Liquid petroleum gas	MJ ha^{-1}	1287.51
Electricity	MJ ha^{-1}	167.11
Natural gas	MJ ha^{-1}	289.57

The distance for transportation of corn grain to a wet milling operation is assumed to be the same as the distance corn grain travels in the ethanol from corn grain production system (Wang 2000). Process information on the corn wet milling process was obtained from Cargill Dow LLC (Vink 2003). Metabolix Inc. (Cambridge, Massachusetts, USA) provided the energy consumption and yield of PHA in the PHA fermentation process (including fermentation and recovery) and specified various technologies as current and near future technologies (van Walsem 2003). The near future technology is an improved process that is achievable over a 2–3 year time horizon, extrapolating from current laboratory results. Along with Metabolix's operating data on the PHA fermentation process, literature data for the PHA fermentation (Gerngross 1999, Akiyama et al. 2003) were also used to identify technology trends in the PHA fermentation process. Information on processing corn stover to PHA can be obtained from Kurdikar et al. (2001).

The electrical power grid for the foreground systems (e.g., corn production, wet milling and PHA fermentation) is estimated from ECAR (East Central Area Reliability Coordination Agreement), MAIN (Mid-America Interconnected Network), and MAPP (Mid–Continent Area Power Pool), which cover these seven states. The data sources are summarized in **Table 2**.

Table 2: Primary data sources

Process	References
Agronomic inputs	National Agricultural Statistics Service (2004)
Fuel requirement in the cropping system	Economic research service (2003)
Climate and soil data in the cropping site	National Oceanic & Atmospheric Administration (2003), Natural Resources Conservation Service (2003)
Soybean milling process	Sheehan et al. (1998)
Fuel consumption for harvesting corn stover	Sheehan et al. (2002)
Dextrose production (wet milling)	Vink (2003)
PHA fermentation and recovery	Van Walsem (2003)
Corn stover conversion to PHA	Kurdikar et al. (2001)
US Electricity production system	Kim and Dale (2004)
Nitrogen fertilizer/ Phosphorus fertilizer	Office of Industrial Technologies (2000), Kim and Overcash (2000), International Fertilizer Industry Association (2001), International Fertilizer Industry Association (1998)
Urea	Office of Industrial Technologies (2000), Pagani and Zardi (1994)
Other data (e.g., fuels, potassium fertilizer, polystyrene, etc.)	DEAM™ LCA database

The greenhouse gases (GHG) evaluated include carbon dioxide, methane, nitrous oxide (N_2O), and other greenhouse gases. The carbon contents (55.8%) in PHA are also taken into account as an environmental credit in the global warming analysis. The GHG evaluation also includes carbon sequestration due to increasing (or decreasing) soil organic carbon and N_2O releases from soil during cultivation. Soil organic carbon and nitrogen dynamics during cultivation are predicted by the DAYCENT model (Parton et al. 1996, Del Grosso et al. 2000, Del Grosso et al. 2001, Parton et al. 2001, Parton et al. 1987, Parton et al. 1988). This model can also predict the effects of disturbances and management practices such as fire, grazing, cultivation, and organic matter or fertilizer addition. Required input parameters for the model include climate information (temperature and precipitation), and site-specific soil properties (soil texture, soil organic content, soil moisture content, and soil mineral content). Climate information is obtained from the National Oceanic & Atmospheric Administration (National Climatic Data Center). Site-specific soil textures are available from the US Department of Agriculture (Natural Resources Conservation Service).

Since other site-specific soil properties (soil organic carbon level, soil nitrogen level, moisture, and mineral contents) are not available, the DAYCENT model is run for 1860 years with default values given by the model to generate the initial site-specific soil properties (Keough 2003). In the initialization used here, native grass is assumed to be cultured up to 1860 years to reach a steady state (the 'spin up' process). After establishing the initial soil properties (e.g., soil organic carbon level, soil nitrogen level, moisture, etc.), the modified crop history of western Iowa given by Kristen et al. (2000) is simulated from 1860 to 1994. The modified crop history of western Iowa is applied here because no information is available on the crop history of each county under consideration. Effects of the crop history on the final results, particularly on greenhouse gas emissions and nitrogen related emissions, are scrutinized in a sensitivity analysis. After completing the model spin-up process (initialization) and the previous cropping system, the effects of continuous corn culture under no-tillage practice are predicted by the model.

Nonrenewable energy from the inventory analysis is defined as a sum of nonrenewable energy used in the process (i.e., fossil energy and electricity) and feedstock energy, and presented as one of the environmental performance indicators. The potential environmental impact categories considered here are global warming impact, acidification, eutrophication and photochemical smog. The characterization factors are obtained through the TRACI model (Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts) developed by the United States Environmental Protection Agency (National Risk Management Research Laboratory 2003).

3 Results and Discussion

3.1 Corn grain-based PHA (reference system)

Two counties in each state were selected to estimate soil organic carbon changes and nitrogen related emissions from soil (e.g., N_2O, NO_x, and NO_3^-). Counties were chosen because they produced significant amounts of corn and because of the availability of other data such as soil textures and weather information. Corn is assumed to be continuously cultured under no-tillage condition for 40 years to estimate carbon taken up by soil and nitrogen related emissions from soil. The climate conditions (e.g., daily temperature and precipitation) are based on weather data from 1997 to 2000. Results from the DAYCENT model show that carbon sequestration rates range from 377 to 681 kg–C ha^{-1} $year^{-1}$ under no-tillage practice, as presented in **Fig. 2**, consistent with the rates given by other studies: 300–600 kg-C ha^{-1} $year^{-1}$ in the US Great Plains (Follett 2001, Robertson et al. 2000).

Fluxes of N_2O from soil during corn culture range from 0.5 to 2.8 kg-N ha^{-1} $year^{-1}$ under no-tillage practice, as shown in **Fig. 3**. The ratio of the flux of N_2O to the application rate of nitrogen fertilizer is from 0.4 up to 1.7%, showing that the flux of N_2O depends strongly on local conditions–e.g., ap-

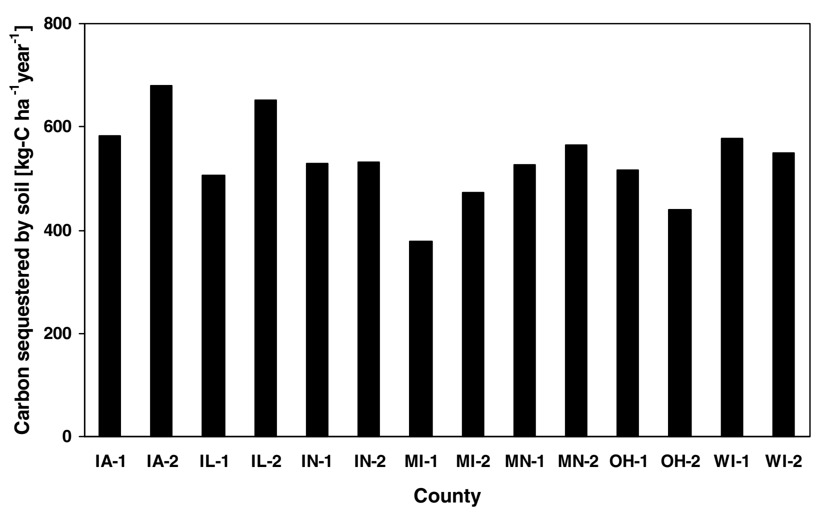

Fig. 2: Carbon sequestered by corn culture under no-tillage practice (IA-1: Pottawattamie county in IA, IA-2: Sioux county in IA, IL-1: Iroquois county in IL, IL-2: McLean county in IL, IN-1: Knox county in IN, IN-2: White county in IN, MI-1: Branch county in MI, MI-2: Lenawee county in MI, MN-1: Blue Earth county in MN, MN-2: Freeborn county in MN, OH-1: Darke county in OH, OH-2: Madison county in OH, WI-1: Dane county in WI, WI-2: Grant county in WI)

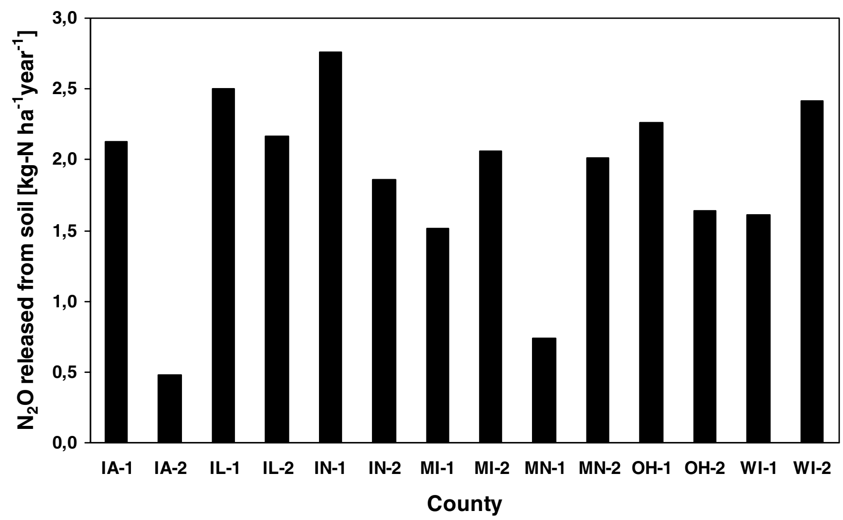

Fig. 3: N_2O emissions from soil during corn cultivation under no-tillage practice

plication rates of nitrogen fertilizer, soil textures, soil nitrogen contents, climate conditions, etc. NO_x emissions from soil ranges from 7.5 to 26.4 kg-NO_x ha^{-1} year^{-1}, and NO_3^- emissions due to leaching are from 0.003 to 18.8 kg-NO_3^- ha^{-1} year^{-1}. The environmental burdens of PHA are presented as average values over 14 counties, weighted by their corn production.

Nonrenewable energy ranges from 69 to 107 MJ kg^{-1}, depending on the PHA fermentation technologies. The highest nonrenewable energy use occurs in the PHA fermentation technology given by Gerngross (1999), which has low PHA yields and high electricity consumption. The PHA fermentation process, which accounts for over 60% of the total nonrenewable energy use, is the primary contributing sub-process because of high electricity consumption in the fermentation operation.

The historical trend of nonrenewable energy use shows that the PHA fermentation technologies are still immature and continue to improve. Improvements in the PHA fermentation technologies, including PHA yield and energy efficiency, reduce overall nonrenewable energy by up to 36% when comparing near future technology given by Metabolix (van Walsem 2003) to PHA fermentation technology given by Gerngross (1999).

The global warming impact associated with the corn grain–based PHA production system is presented in **Fig. 4**, in which the legends refer to the different sources of operating data for the PHA fermentation technologies. The global warming of PHA range from 1.6 to 4.1 kg-CO_2 eq. kg^{-1}, demonstrating that changing the PHA fermentation technologies reduces GHG emissions by up to 62%. The avoided systems in **Fig.** 4 comes from alternative product systems for coproducts in the corn wet milling process and varies among the different PHA fermentation technologies, –0.48 to –0.63 kg-CO_2 eq. kg^{-1}. The lowest global warming occurs in the PHA fermentation technology given by Akiyama et al. (2003), which also features the lowest electricity consumption. The PHA fermentation technology given by Gerngross (1999) has the highest global warming due to low yield of PHA and high electricity consumption.

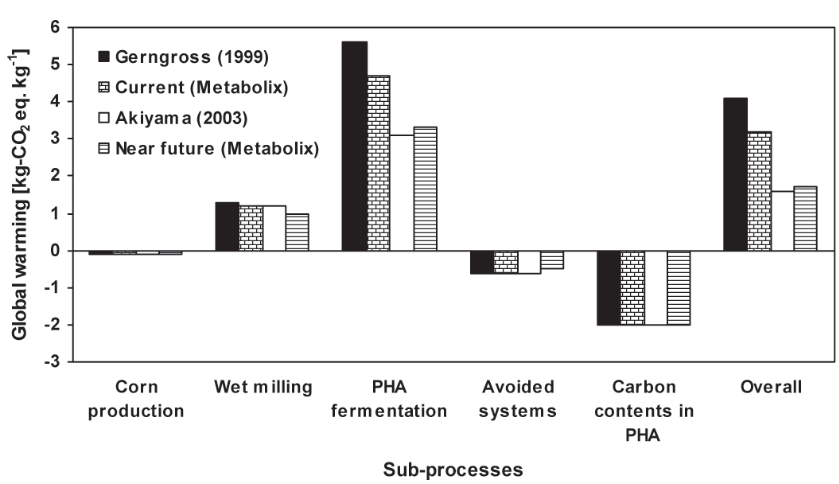

Fig. 4: Global warming in the PHA production system based on 100-year time horizon global warming potentials (Intergovernmental Panel on Climate Change 2001) [Gerngross (1999): PHA fermentation technology given by Gerngross (1999), Current (Metabolix): PHA fermentation technology given by Metabolix Inc. (van Walsem 2003), Akiyama (2003): PHA fermentation technology given by Akiyama et al. (2003), Near future (Metabolix): PHA fermentation technology given by Metabolix Inc. (van Walsem 2003)] Note: PHA fermentation includes fermentation and recovery

Table 3: Photochemical smog, acidification and eutrophication associated with corn grain-based PHA

	Corn production	Wet milling	PHA fermentation	Avoided systems	Overall
Photochemical smog [mg–NO_x eq. m^{-1} kg^{-1}]					
Gerngross (1999)	21.8	3.54	16.4	–11.1	30.7
Current (Metabolix)	21.3	3.45	13.8	–10.8	27.7
Akiyama (2003)	20.7	3.36	8.98	–10.5	22.5
Near future (Metabolix)	16.4	2.66	9.79	–8.30	20.6
Acidification [moles H^+ eq. kg^{-1}]					
Gerngross (1999)	0.91	0.30	1.67	–0.47	2.41
Current (Metabolix)	0.89	0.30	1.41	–0.46	2.14
Akiyama (2003)	0.86	0.29	0.92	–0.44	1.62
Near future (Metabolix)	0.68	0.23	1.00	–0.35	1.56
Eutrophication [g–N eq. kg^{-1}]					
Gerngross (1999)	2.19	0.12	0.59	–0.89	2.02
Current (Metabolix)	2.14	0.12	0.51	–0.86	1.90
Akiyama (2003)	2.08	0.12	0.32	–0.84	1.68
Near future (Metabolix)	1.65	0.09	0.36	–0.66	1.43

Most GHG emissions come from the PHA fermentation and recovery process, which is energy-intensive. Among the energy sources, electricity consumption in the PHA fermentation and recovery process is the primary GHG emission source because a high fraction of electricity is generated by coal–fired power plants in the Corn Belt states of the United States. The negative GHG emissions (GHG credits) in corn production are associated with the increase in soil organic carbon level under no-tillage conditions, which could sequester 1.0–1.4 kg-CO_2 kg^{-1}, while N_2O emissions from soil during corn production range from 10 to 13 g kg^{-1}. The avoided GHG emissions associated with the alternative product systems depend on the yield of PHA by fermentation, resulting in 0.5–0.6 kg-CO_2 eq. kg^{-1}. The greenhouse gas credit due to carbon content in PHA is about 2 kg kg^{-1}.

Photochemical smog, acidification and eutrophication associated with corn grain-based PHA are summarized in **Table 3**. In photochemical smog and eutrophication, corn cultivation is the primary contributing process due to nitrogen related emissions (NO_x and NO_3^-) from soil during corn cultivation. The PHA fermentation process contributes more to acidification than other processes because of NO_x and SO_x emissions from process energy used. The lowest impact on photochemical smog, acidification and eutrophication occurs in the near future technology given by Metabolix Inc.

3.2 Integrated system

Harvesting corn stover may result in lower soil organic carbon levels and soil nitrogen contents, and may also increase soil erosion (Mann et al. 2002). Some authorities recommend that approximately 30% of the soil surface should be covered with crop residues after harvest to reduce soil erosion by wind (Padgitt et al. 2000). A 30% ground cover requires 1.07 Mg of corn stover per hectare (Renard et al. 1997). The quantity of corn stover for covering the ground depends on site-specific factors (e.g., slope, climate etc.), and the 30% ground cover specification is currently being debated (Mann et al. 2002). For this study, 60% of corn stover is removed to maintain soil erosion at a tolerable level, resulting in more than 3 ton of corn stover per hectare left in cornfield, which is more than twice the minimum recommended cover (Renard et al. 1997). The effects of soil erosion therefore are not taken into account in this study. Under the 60% corn stover removal scenario, annual carbon sequestered by soil per hectare is predicted to be reduced by 37–53%, compared to carbon sequestered by soil without corn stover removal. Thus, removing corn stover lowers the accumulation rate of soil organic carbon.

In the integrated system, corn stover as well as corn grain are used as raw materials for PHA production, and lignin-rich residues are utilized to generate electricity and steam that are used in the PHA fermentation processes. One kg of PHA derived from corn stover along with corn grain requires 3.1–3.7 m^2 of arable land, while one kg of PHA derived from corn grain only requires 4.4–5.8 m^2 of arable land. When an integrated system has surplus energy from burning lignin-rich residues, surplus steam could be exported to replace energy used in a district heating system, in which natural gas is assumed to be the energy source, and surplus electricity would be exported to a regional power grid.

The PHA production system under the technology given by Gerngross (1999) exports only steam because the electricity requirement in the PHA fermentation is higher than electricity generated from burning lignin-rich residues. A similar situation is observed in the PHA production system under the current technology given by Metabolix Inc. PHA production technologies given by Metabolix Inc. (near future) and by Akiyama et al. (2003) export both surplus steam (via district heating) and electricity. The exported electricity from the PHA production system is assumed to replace electricity from a coal-fired power plant, from a natural gas-fired power plant or from a petroleum oil-fired power plant.

Table 4: Nonrenewable energy in the integrated system

	Corn production	Harvest and transportation for corn stover	Wet milling	PHA fermentation	Corn stover process	Avoided systems	Avoided electricity	Avoided steam	Overall
Nonrenewable energy [MJ kg^{-1}]									
Gerngross (1999)	9.43	1.57	13.0	15.3	–	–4.34	–	–3.44	31.5
Current (Metabolix)	9.28	1.54	12.8	6.08	–	–4.27	–	–0.53	24.9
Akiyama (2003)	9.11	1.51	12.6	5.13	–	–4.19	–11.71	–0.15	12.3
Near future (Metabolix)	7.77	1.29	10.7	2.88	–	–3.58	–0.0007	–1.28	17.8

These fossil fuel based power plants can more easily manipulate their generation capacity than nuclear and hydro power plants. The avoided burdens of alternative product systems are introduced to allocate the benefits for the surplus energy. Electricity production from a coal-fired power plant is considered as a base case. We also scrutinize the effects of the choice of the alternative product systems for the exported electricity in a sensitivity analysis.

Even though utilizing corn stover requires more nonrenewable energy in harvesting and transporting corn stover, the integrated system (corn grain and corn stover utilized as raw materials for PHA production) can conserve nonrenewable energy by 70–84% when compared to the reference system (corn grain-based PHA production system). The reductions in nonrenewable energy in the integrated system are because of 1) a higher production rate of PHA per hectare, and 2) electricity and steam generated from burning lignin-rich residues. **Table 4**, in which a coal-fired power plant is the alternative product system, summarizes nonrenewable energy in the integrated system.

Global warming impact per kg of PHA produced in an integrated system is –0.28 kg-CO_2 eq. kg^{-1} in the technology given by Gerngross (1999), –0.77 kg-CO_2 eq. kg^{-1} in the current Metabolix technology, –1.19 kg-CO_2 eq. kg^{-1} in the near future Metabolix technology, and –1.93 kg-CO_2 eq. kg^{-1} in the technology given by Akiyama et al. (2003). Thus the integrated system offers a global warming credit (negative global warming) regardless of PHA fermentation technologies even though the accumulation rate of SOC associated with the removal of corn stover is predicted by the model to be less than in the no corn stover removal case. The PHA production technology given by Akiyama et al. (2003) provides the greatest global warming credit because of the largest surplus electricity exported. Global warming in the integrated system is illustrated in **Fig. 5**, in which a coal-fired power plant is the alternative electricity generation system.

Other environmental impacts in the integrated system are summarized in **Table 5**. The integrated system can reduce photochemical smog, acidification and eutrophication, compared to the reference system (corn grain-based PHA production system). The reduction in these environmental impacts is because less energy is used in the PHA fermentation process due to energy generated by combusting lignin-rich residues. Corn cultivation is the primary contributing process to these environmental impacts in the integrated system.

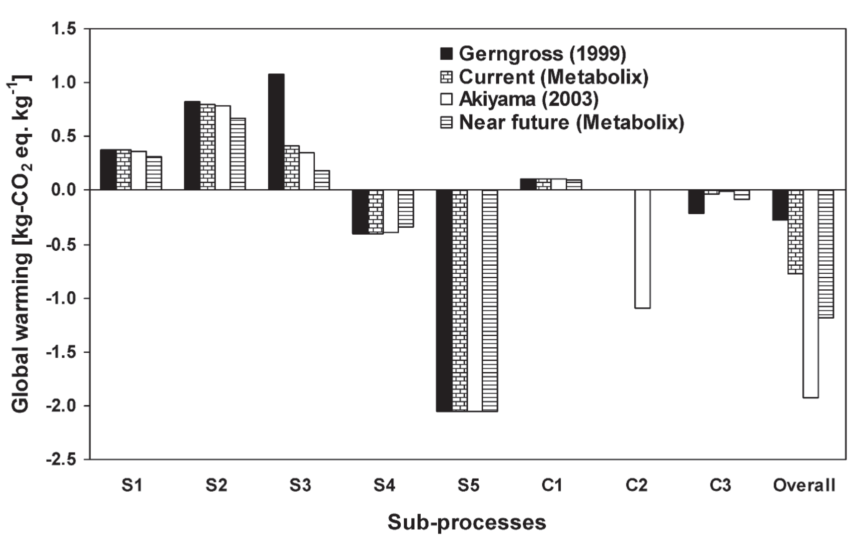

Fig. 5: Global warming associated with PHA produced in the integrated system. [S1: corn production and transportation for corn, S2: wet milling, S3: PHA fermentation and recovery (corn grain), S4: avoided systems for coproducts in the wet milling process, S4: Carbon content in PHA, C1: harvest and transportation for corn stover, C2: surplus electricity exported, C3: surplus steam exported]

Table 5: Other environmental impacts in the integrated system

	Photochemical smog [mg–NO_x eq. m^{-1} kg^{-1}]	Acidification [moles H^+ eq. kg^{-1}]	Eutrophication [g–N eq. kg^{-1}]
Gerngross (1999)	16.4	0.97	1.21
Current (Metabolix)	14.6	0.81	1.14
Akiyama (2003)	10.2	0.36	0.98
Near future (Metabolix)	11.7	0.62	0.94

3.3 Sensitivity analysis

Four factors are considered in the sensitivity analysis: 1) tillage practice, 2) previous crop history, 3) allocation procedures, and 4) the alternative electricity generation system. Effects of the first two factors are estimated in the reference system, and effects of the third one are focused on both the reference and the integrated systems. Effects of the final factor are obtained only for the integrated system.

3.3.1 Effects of tillage practices

Using corn grain cultured under plowing tillage (in which soil is plowed before planting) as a raw material for PHA would increase global warming associated with the PHA production system by 29–46%. Global warming estimates in the PHA production system under plowing tillage are 7.9 kg-CO_2 eq. kg^{-1} in the technology given by Gerngross (1999), 7.0 kg-CO_2 eq. kg^{-1} in the current technology (Metabolix Inc.), 5.3 kg-CO_2 eq. kg^{-1} in the technology given by Akiyama (2003), and 5.1 kg-CO_2 eq. kg^{-1} in the near future technology (Metabolix Inc.). Soil organic carbon levels in corn cultivation under plowing tillage practice decrease at a rate of 2.1–97 kg-C ha^{-1} $year^{-1}$. The plowing tillage practice also increases nonrenewable energy in the PHA production system by up to 6% because of higher potassium fertilizer application rate and more fuel required than no-tillage practice, but less phosphorus fertilizer rate and herbicide use (Christensen 2002, West and Marland 2002). Corn yields under no-tillage and plowing tillage are not significantly different. Higher potassium application rates and greater fuel requirements in plowing tillage increase the potential environmental impacts of the PHA production system. The tillage practices (till vs. no-till) have more effect on global warming and photochemical smog of the PHA production system, but less on nonrenewable energy, acidification and eutrophication.

3.3.2 Effects of previous crop history

Different previous crop histories might affect global warming, photochemical, acidification and eutrophication of the PHA production system. For example, soil organic carbon and soil nitrogen dynamics depend on the crop history, which determines the initial soil properties, e.g., soil organic carbon profile, soil nitrogen, moisture content, etc. As mentioned, our previous simulations used the modified crop history of western Iowa from 1860 to 1994, prior to beginning continuous corn cultivation. Here we scrutinize the effects of different previous cropping systems on global warming, photochemical smog, acidification, and eutrophication. Additional previous cropping systems used in this sensitivity analysis include the crop histories of north eastern Iowa (Brenner et al. 2001) and of north central Indiana (Smith et al. 2002). Details of the application rate of nitrogen fertilizer and the harvest methods are available in each reference. The sensitivity analysis has been done in such a way that each previous cropping system is applied from 1860 to 1994 before simulating continuous corn cultivation.

There are no significant predicted differences in the quantities of carbon taken up by the soil between the three crop histories, but nitrogen related emissions from soil (N_2O, NO_x, NO_3^-) vary slightly with the previous crop history. The sensitivity analysis shows that the effects of the previous cropping system on the four environmental impacts of the PHA production system are not significant. For example, global warming associated with corn grain based PHA produced by the near future technology (Metabolix, Inc.) range from 1.69 to 1.71 kg-CO_2 eq. kg^{-1} depending on the crop history. Thus, the crop histories investigated in this study would not significantly affect the final results.

3.3.3 Effects of allocation procedure

The environmental burdens associated with dextrose in the corn wet milling process have been estimated by the system expansion approach (ISO 1998) introducing the alternative product systems for its coproducts (i.e., CGM, CGF, corn oil). There are several allocation procedures to estimate the environmental burdens associated with dextrose (e.g., physical property based and economic value based allocation procedures). In this study, an output mass based allocation procedure is used to estimate the effects of the allocation procedure in the wet milling process on the final results.

In the output mass based allocation, about 70% of the environmental burdens of corn production and wet milling process are allocated to dextrose. In the reference system (corn grain based PHA), the differences between all the impact categories in the system expansion approach and the output mass based allocation are less than 20%. Similar patterns in most impact categories are observed in the integrated system. **Table 6** summarizes the potential environmental impacts of PHA (produced by the near future Metabolix technology) estimated by the system expansion approach and the output mass based allocations.

Table 6: Environmental impacts estimated by the system expansion approach and the output mass based allocations

Impact category	Unit	Reference system		Integrated system	
		System expansion	Mass allocation	System expansion	Mass allocation
Near future (Metabolix)					
Nonrenewable energy	[MJ kg^{-1}]	68.6	66.0	17.8	15.8
Global warming	[kg–CO_2 eq. kg^{-1}]	1.72	1.92	–1.19	–1.15
Photochemical smog	[mg–NO_x eq. m^{-1} kg^{-1}]	20.5	23.1	11.7	13.5
Acidification	[moles H^+ eq. kg^{-1}]	1.56	1.64	0.62	0.67
Eutrophication	[g–N eq. kg^{-1}]	1.43	1.57	0.94	1.03

3.3.4 Effects of alternative electricity system

The alternative electricity system for surplus electricity in the corn stover process has been assumed to be electricity generated from a coal-fired power plant in the integrated system. It is also possible that electricity generated from a natural gas-fired power plant or from a petroleum oil-fired power plant is replaced by electricity exported from the corn stover process. There are no significant differences in the near future Metabolix technology due to the small quantity of electricity exported. The differences between most impacts caused by the choice of the avoided electricity systems are less than 20% in the technology given by Akiyama et al. (2003) except for acidification. The differences of SO_x emissions in power plants are the primary factor in acidification.

3.4 Comparisons with petroleum based polymer

Heyde (1998) concluded that a film made of PHA could replace a film made of polyethylene (PE) or polystyrene (PS), and the same mass or less of PHA would be required to fulfill an equivalent function delivered by polystyrene. In this study, polystyrene is chosen to compare the environmental impacts between PHA and petroleum based polymer. The comparisons are done assuming mass equivalency (i.e., 1 kg PHA equivalent to 1 kg of PS resin) (Heyde 1998). The cradle-to-gate life cycle inventory (LCI) data for polystyrene production system is obtained from a commercial LCI database (Ecobilan, DEAM™). Since physical property based allocation has been used in the polystyrene production system, the environmental impacts derived from output mass based allocation in the PHA production system are compared to those in the polystyrene production.

In the technology given by Akiyama et al. (2003) and the near future Metabolix technology, PHA derived from only corn grain (reference system) is more favorable than PS in terms of nonrenewable energy and global warming. However, other environmental impacts associated with PHA produced in the reference system are greater than those of polystyrene. In the integrated system, PHA produced by all the technologies offers better environmental impacts than polystyrene for all impacts except eutrophication. **Fig. 6** shows global warming associated with producing polymers.

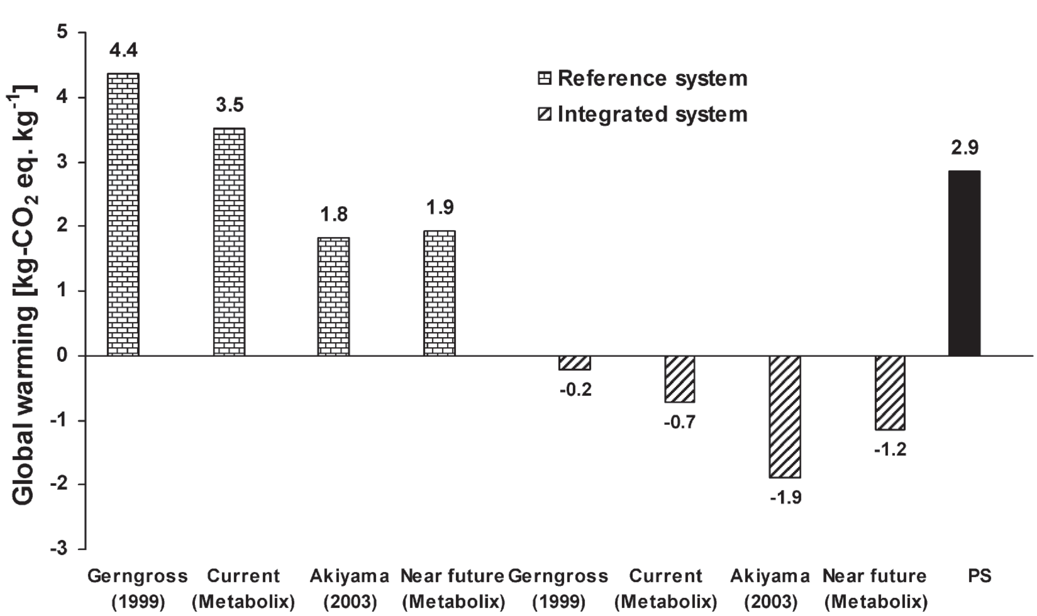

Fig. 6: Comparison of global warming between PHA and PS (based on a mass equivalency)

4 Conclusions and Outlook

Corn grain based PHA produced by the current technology does not offer environmental advantages over polystyrene. However, PHA production technologies are improving. This is the same pattern found in the development of other products, including petroleum-derived products when these were immature. In near future, corn grain based PHA would be more favorable than polystyrene in terms of nonrenewable energy and global warming due to improvements in the PHA fermentation and recovery process.

However, corn grain based PHA produced in even the near future technology does not provide better profiles of other environmental impacts (i.e., photochemical smog, acidification and eutrophication) than polystyrene. One of the primary reasons for high impacts of PHA in photochemical smog, acidification and eutrophication is the environmental burdens associated with corn cultivation. Thus other approaches to reduce these burdens in the agricultural process (e.g., use of buffer strips, etc.) are necessary to achieve better profiles for photochemical smog, acidification and eutrophication associated with corn cultivation.

Although removing corn stover is somewhat less favorable in terms of soil organic matter accumulation rates, utilizing corn stover as a raw material for PHA along with corn grain in an integrated system could significantly decrease the environmental impacts in the PHA production system. The integrated system could produce PHA that provides much smaller environmental impacts (except for eutrophication) than polystyrene. Although no commercial corn stover based PHA is available, an integrated PHA production system could provide large environmental benefits in several categories. Thus more research on integrated production systems is needed.

The reduction of GHG emissions by burning lignin-rich residues is much higher than the increase of GHG emissions resulting from decreasing the accumulation rate of SOC due to removal of corn stover. However, the utilization of corn stover gives rise to a trade-off between local concerns and regional (or global) concerns. Soil quality is probably a more important local issue, while global warming associated with the PHA production system is probably more important regional/global issues. Therefore, a consensus among interested parties (e.g., farmers, local government, national government, environmentalists, manufacturers, etc.) should be reached to guide the utilization of corn stover.

Comparing current Metabolix PHA fermentation technologies to their projected near future technology, the environmental impacts are reduced by over 25%. These improvements are achieved by increasing PHA yields by 23% and reducing energy requirements (electricity and steam) by about 30%. This trend indicates that PHA fermentation technology, an energy intensive process, is still immature and has considerable room for further improvements, leading toward better PHA environmental performance. Studies such as the present one may help PHA manufacturers improve the overall environmental performance of their products by focusing on the most sensitive parts of the system, for example; increasing energy efficiency (or PHA yield) in the PHA fermentation process, asking farmers to use more sustainable practices, and working toward an integrated (corn stover utilizing) system.

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